ADVANCED CONTROL TECHNIQUES AND HIGH PERFORMANCE DISCHARGES IN DIII–D

by

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NATIONAL FUSION FACILITY
SAN DIEGO

208-04/AK/jy

DIII–D PROGRAM FOCUS IS ADVANCED TOKAMAK PHYSICS OPERATION

- Goals of Advanced Tokamaks (AT) include
  - High fusion power density
    ⇒ Improved stability ⇒ high β (β ~ pressure/B^2)
  - Steady state, low recirculating power
    ⇒ Self-generated bootstrap current ⇒ high $\beta_N q$ [$\beta_N \equiv \beta/(I/aB) > 4$]
  - Compact, high fusion gain
    ⇒ Improved confinement ⇒ high $\beta_N\, H_{89P}$ [$H_{89P} > 3$]

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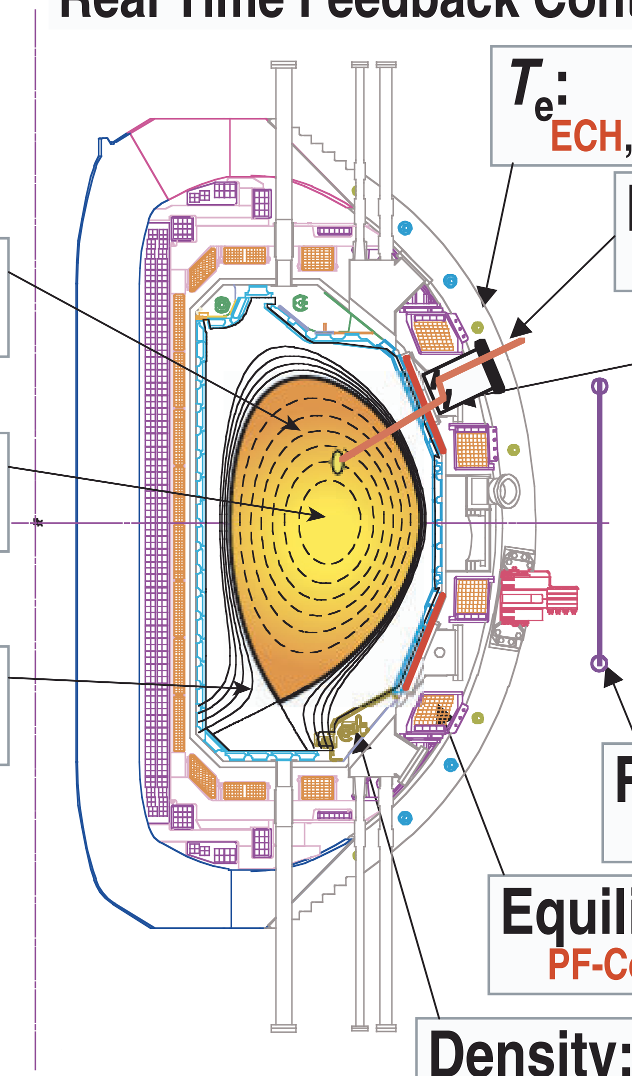
RECENT ADVANCES IN PLASMA CONTROL ON DIII–D HAVE PERMITTED SIGNIFICANT PROGRESS TOWARD THE GOAL OF AN ADVANCED TOKAMAK

- Improved electron cyclotron system for current drive, pressure profile control, and feedback control of plasma instabilities
- Progress toward a fully integrated high performance plasma
  - 100% non-inductive current at $\beta_N < 3.5$
- Stabilization of performance limiting plasma instabilities using rotation (RWM), magnetic coils (RWM, ELMs), and rf techniques (NTM)
- Successful demonstration of disruption mitigation
- Integrated plasma control system

A WIDE RANGE OF CONTROL SYSTEMS HAVE BEEN DEVELOPED TO ENABLE *AT* PERFORMANCE

Real Time Feedback Controlled (Actuator, Sensor)



T_e: ECH, ECE

NTM: ECCD, magnetics

Disruption: Gas jet, magnetics, bolometers

Pressure profile (ITB, Te): ECH,ECCD,ECE

Current Profile: ECCD,ECH,MSE

NBI

Plasma β: P_{aux}, RTEFIT

Edge Stability I-coil, Counter NBI

RWM: C-Coil, I-Coil, magnetics

Equilibrium: PF-Coils, RTEFIT

Density: Pellet/Cryopumps/Gas valves, CO_2 Interferometers

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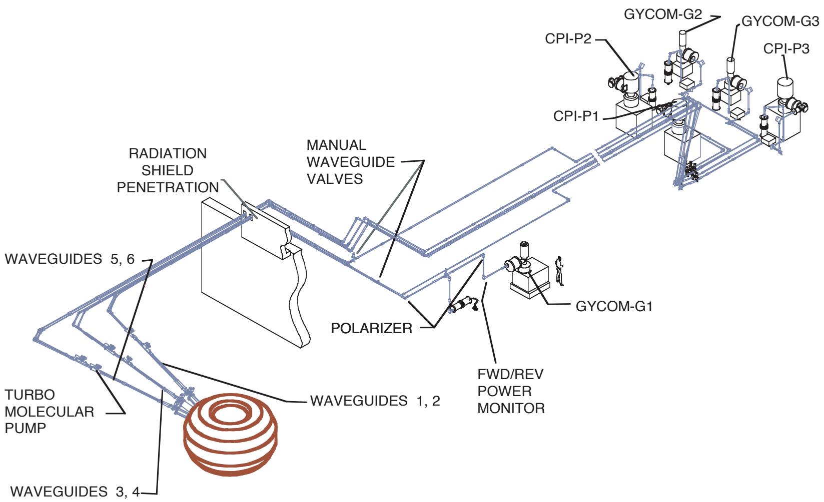
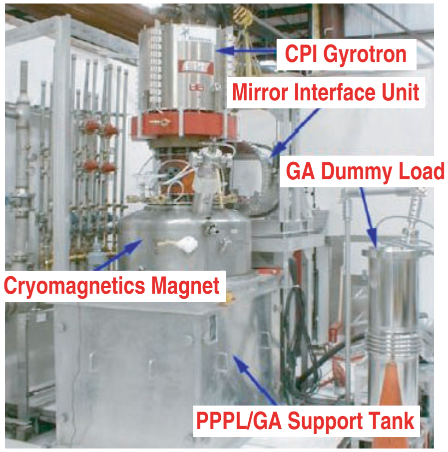
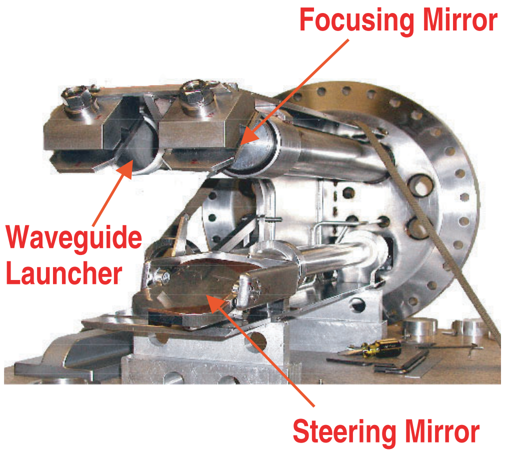
ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE SYSTEM IS A FLEXIBLE TOOL FOR ACHIEVING ADVANCED TOKAMAK PERFORMANCE



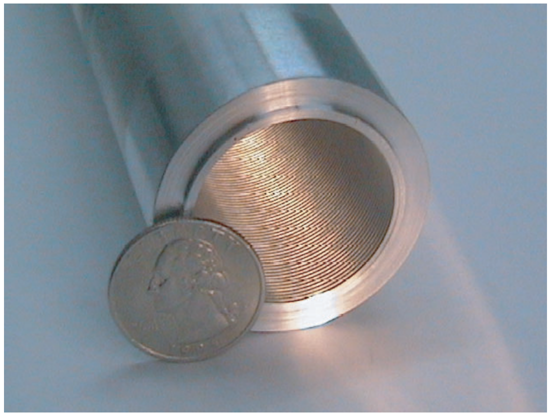
110 GHz EC System Layout



High Power Gyrotrons



EC Launchers



Low Loss Corrugated Waveguides

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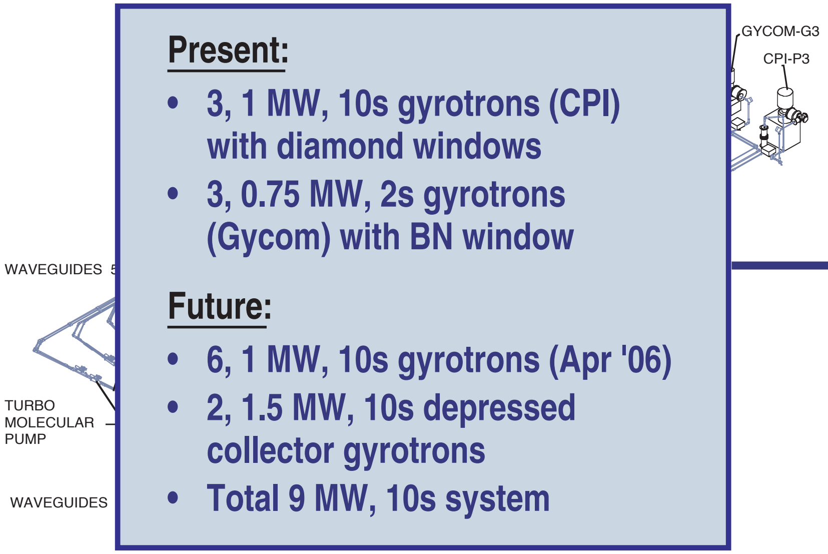
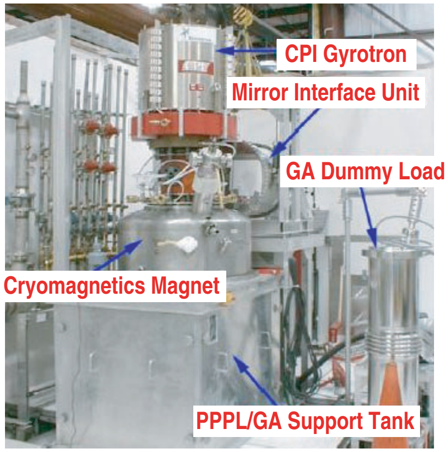


Present:

- 3, 1 MW, 10s gyrotrons (CPI) with diamond windows
- 3, 0.75 MW, 2s gyrotrons (Gycom) with BN window

Future:

- 6, 1 MW, 10s gyrotrons (Apr '06)
- 2, 1.5 MW, 10s depressed collector gyrotrons
- Total 9 MW, 10s system



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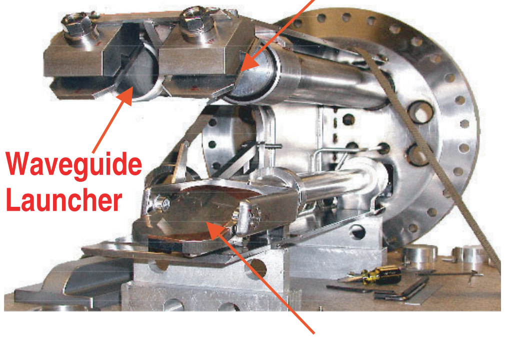
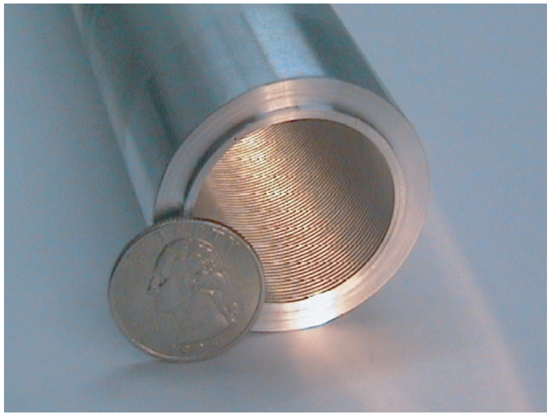


EC Launchers



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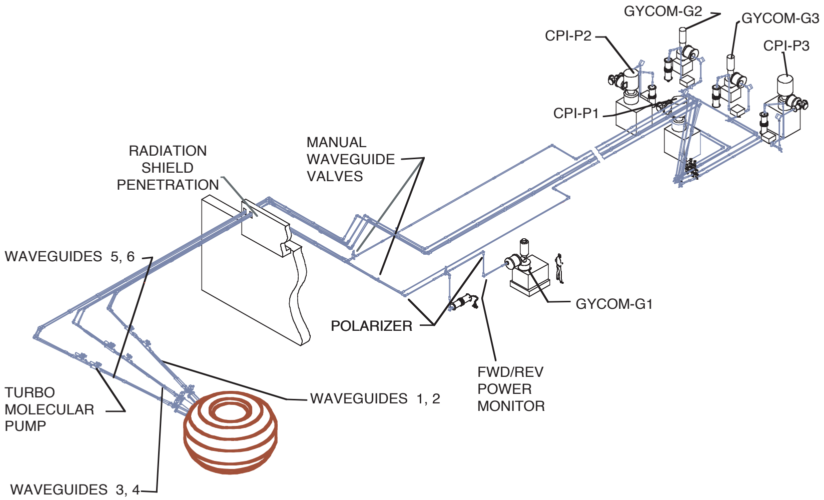
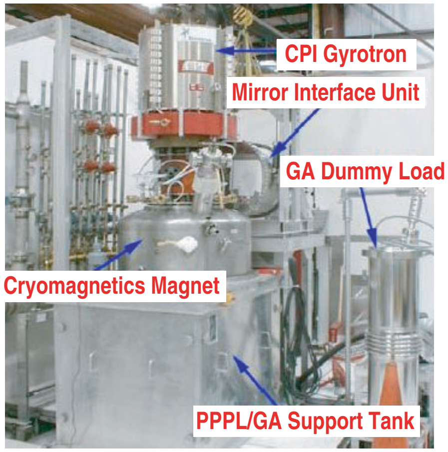


110 GHz EC System Layout



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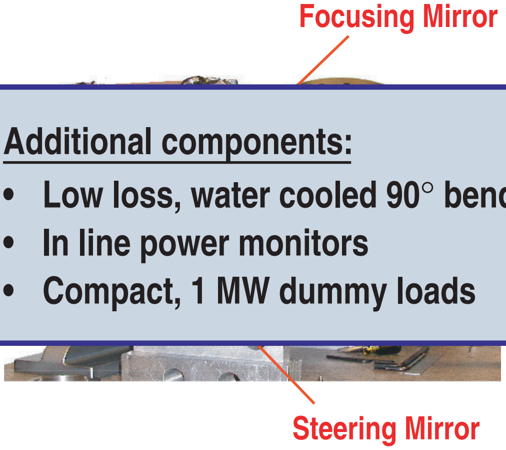
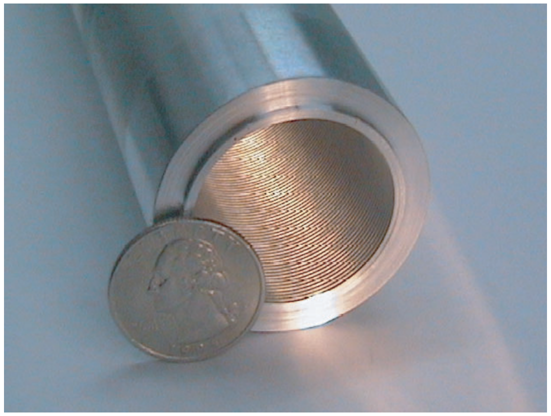


Additional components:

- Low loss, water cooled 90° bends
- In line power monitors
- Compact, 1 MW dummy loads

EC Launchers



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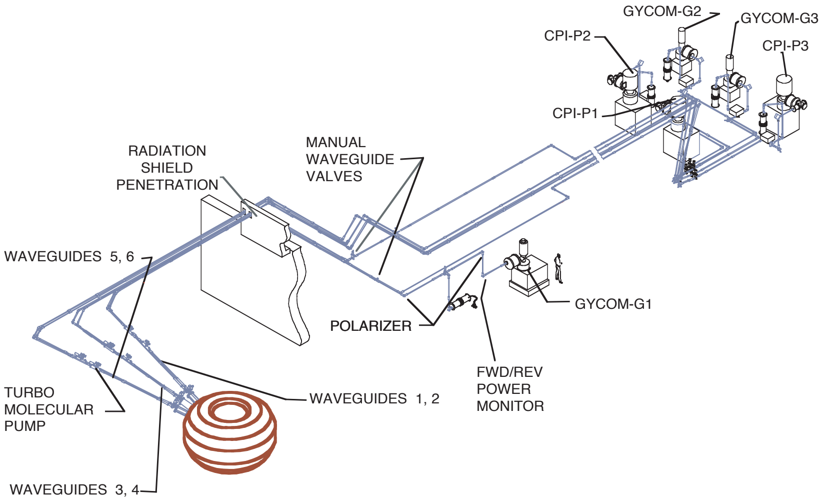

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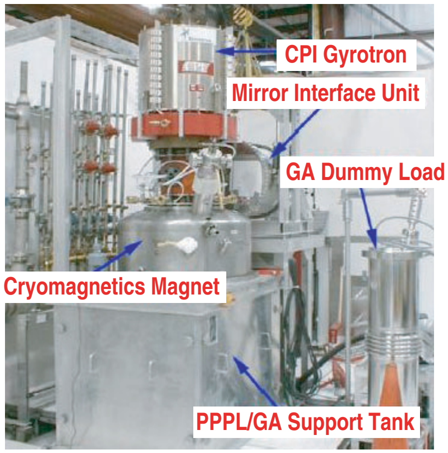

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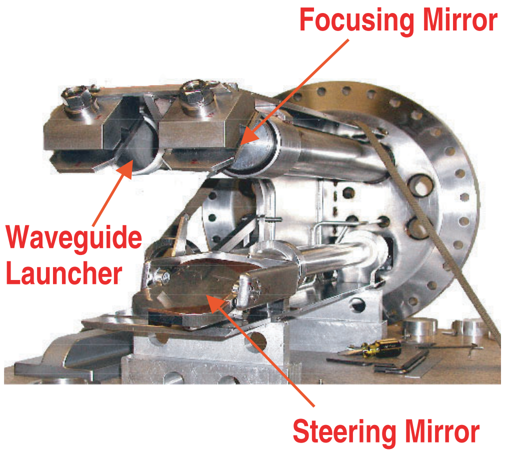
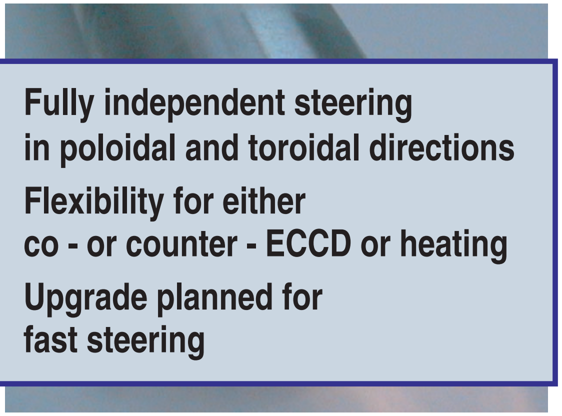


EC Launchers



- Fully independent steering in poloidal and toroidal directions
- Flexibility for either co - or counter - ECCD or heating
- Upgrade planned for fast steering

Low Loss Corrugated Waveguides

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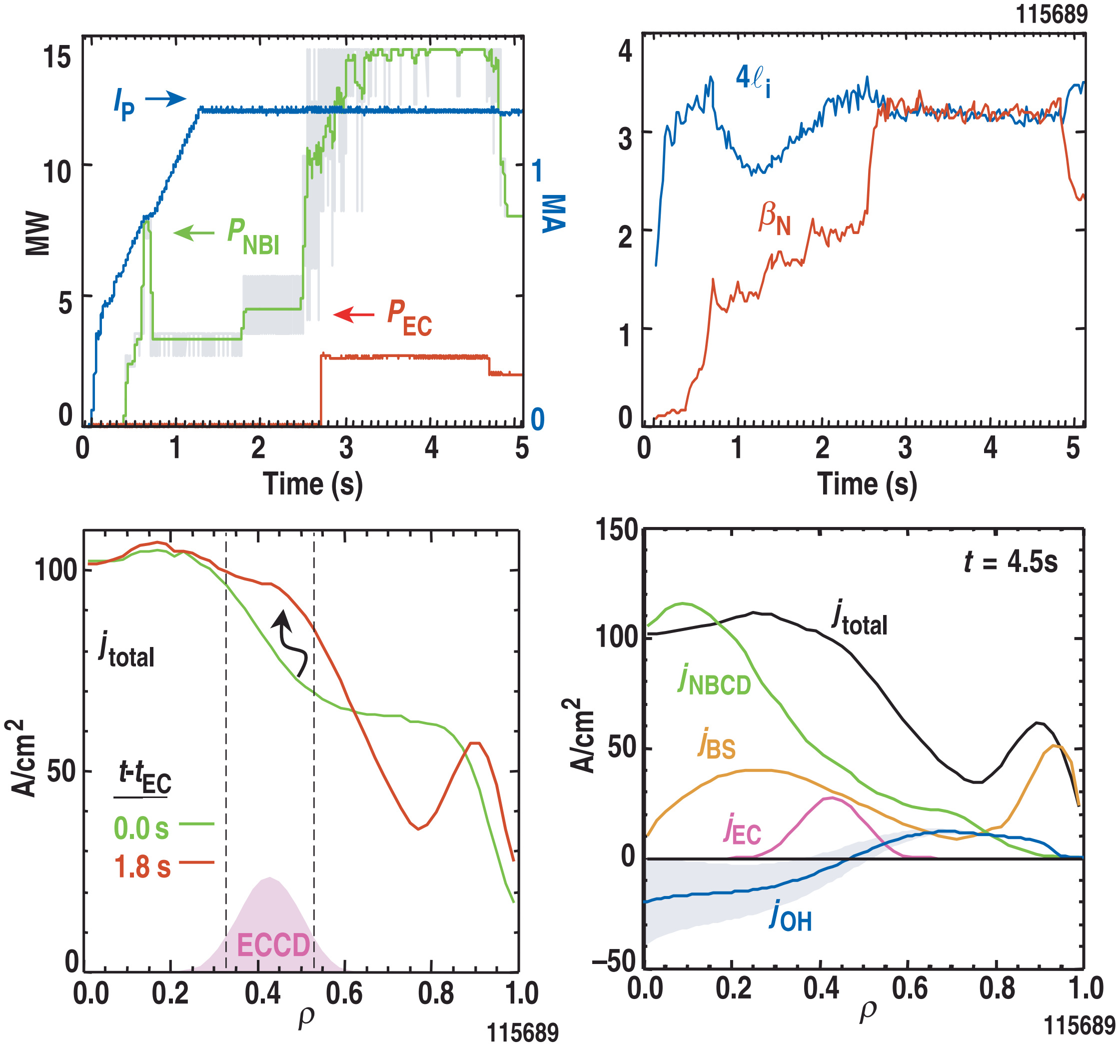
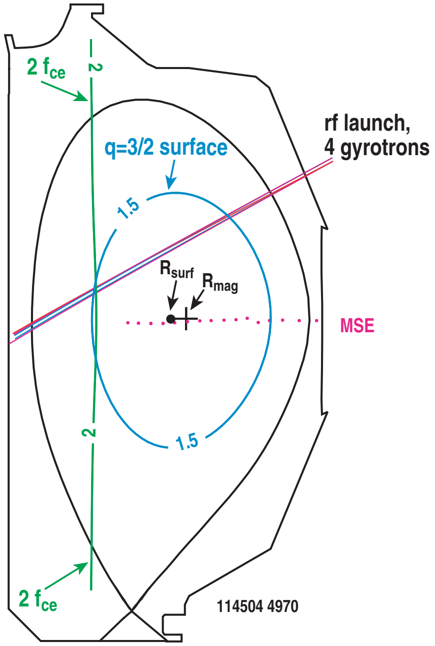
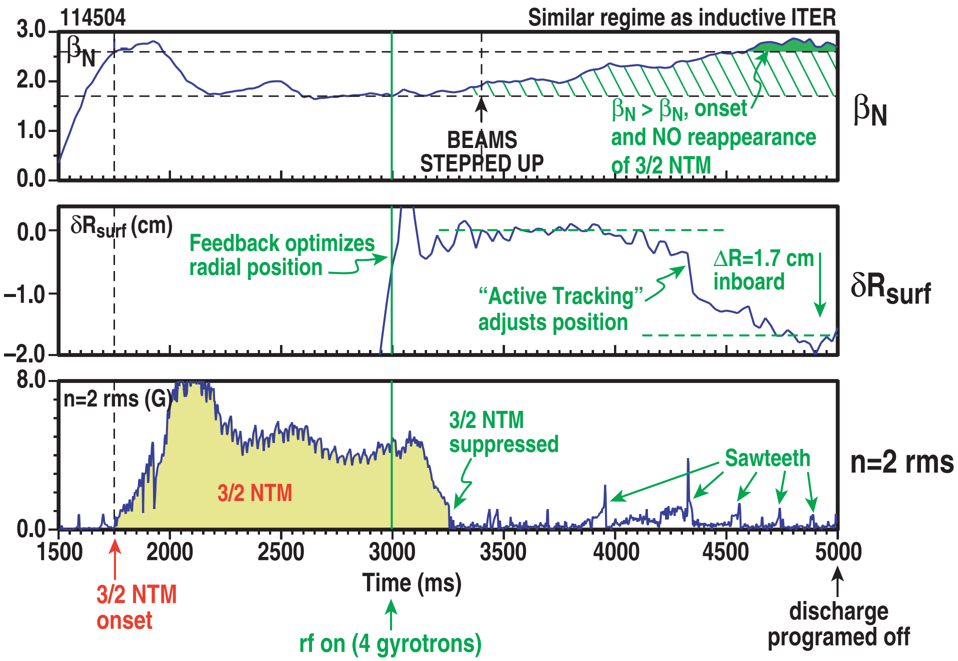
USING OFF-AXIS ECCD, 100% NON-INDUCTIVE CURRENT ACHIEVED AT HIGH BETA, $\beta_N < 3.5$

- $f_{NI} \approx 100\%$ sustained for 2 seconds
  - Consistent with simulations
- High bootstrap fraction $f_{bs} \sim 50\%$
- Profiles undergo significant evolution after ECCD application



ECCD STABILIZES NEO-CLASSICAL TEARING MODES





- "Search and Suppress" adjusts Rsurf to align q=3/2 surface with EC resonance layer and suppress instability
- "Active tracking" keeps ECCD aligned in absence of mode
  - 3/2 location tracked using either neural network or real time calculation using MSE diagnostic
- Stabilization of both 3/2 and 2/1 modes achieved
- Early ECCD used to avoid onset of mode

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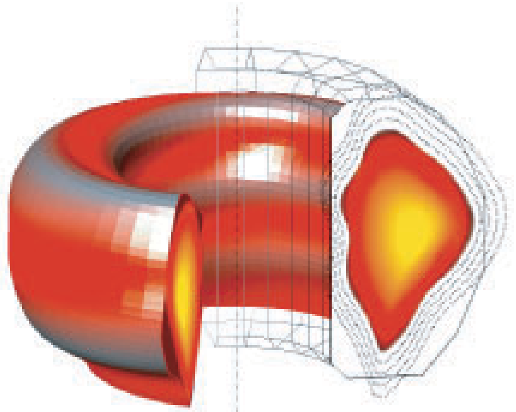
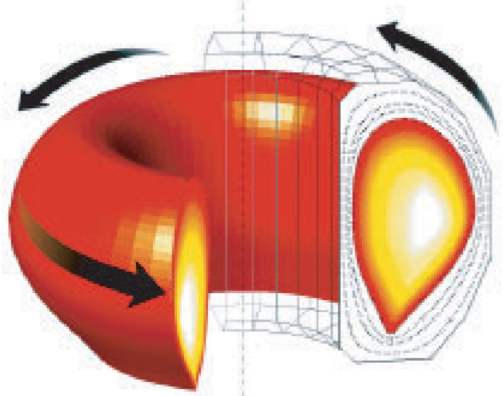
RESISTIVE WALL MALL INSTABILITY AT HIGH β IS PREVENTED BY RAPID PLASMA ROTATION PAST A CONDUCTING WALL

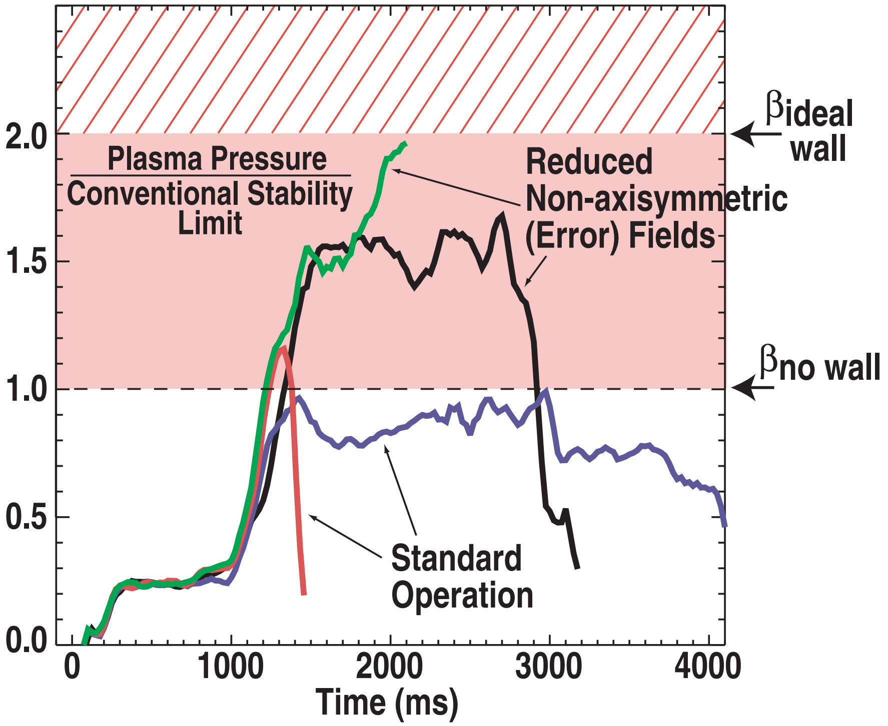


Unstable (x10 Exaggerated)



Stable

- External coils reduce error fields (reduce magnetic drag) and permit neutral beam to induce rapid rotation



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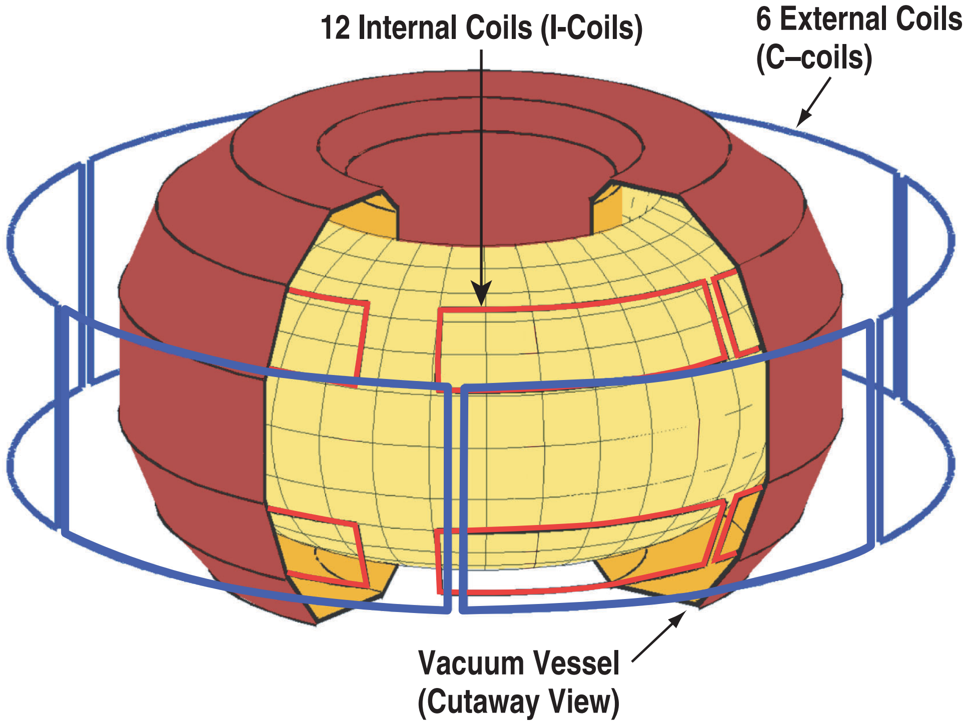
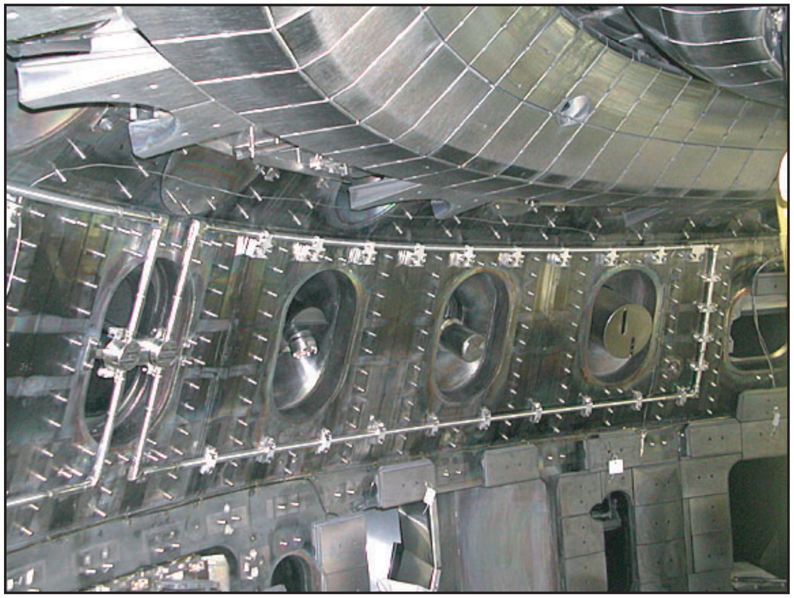
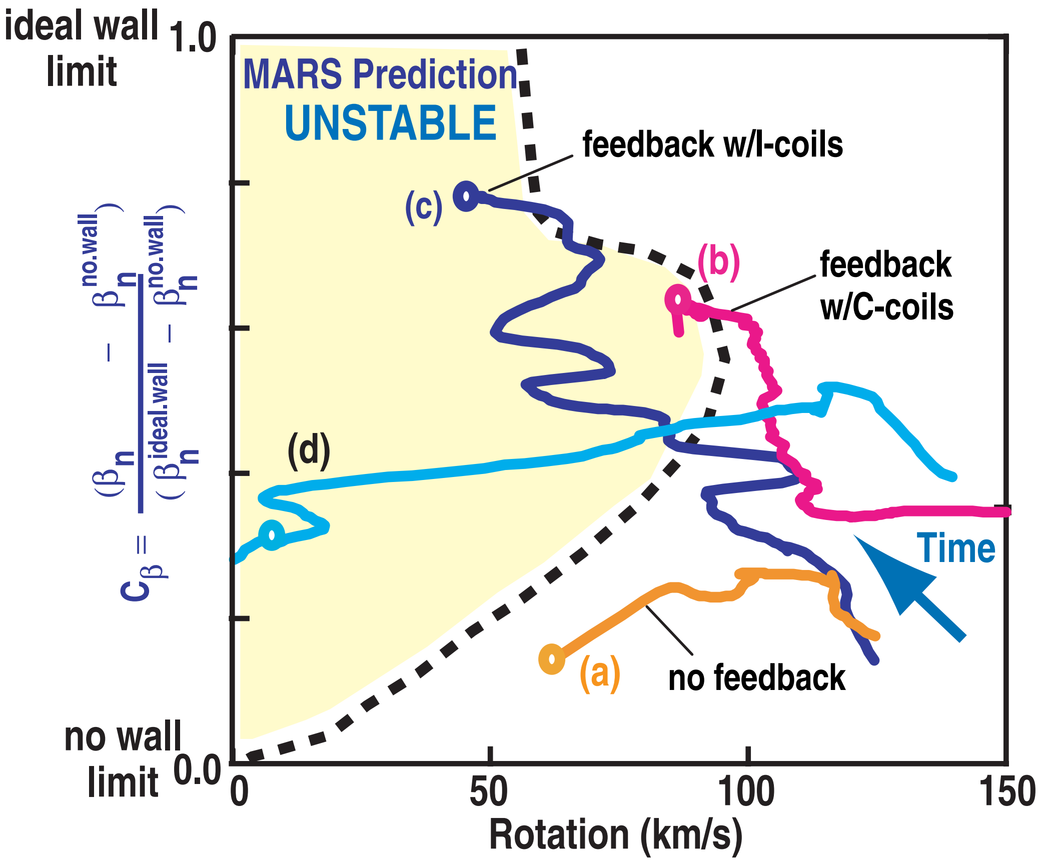
BOTH EXTERNAL AND INTERNAL CONTROL COILS ARE EFFECTIVE TOOLS FOR STABILIZATION OF THE RESISTIVE WALL MODE (RWM)





- Internal coils provide faster time response for feedback control
- Closer to plasma: more efficient coupling, better match to RWM
- 12 single-turn, water-cooled, steady state design
- Protected by graphite tiles
- Wide range of field configurations possible

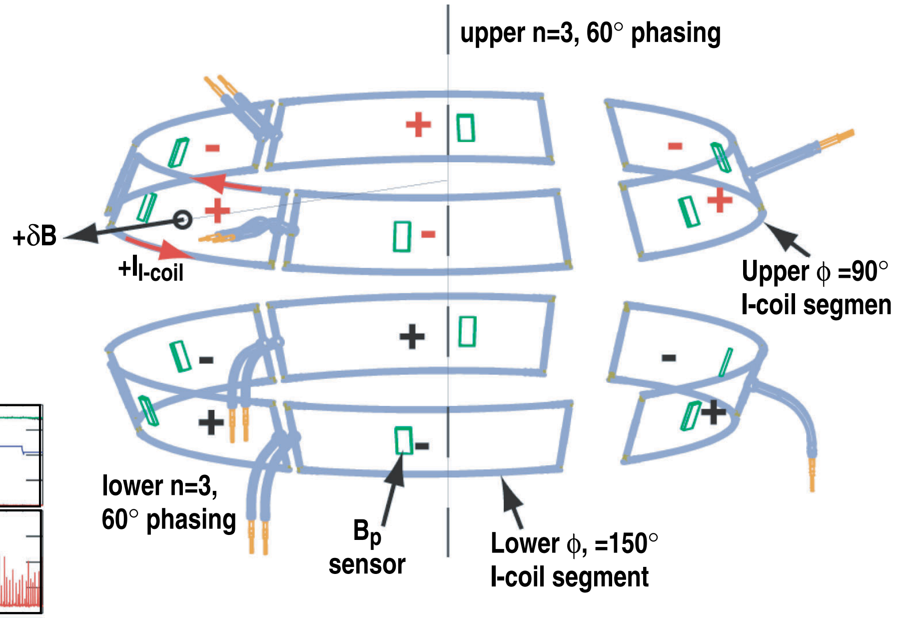
INTERNAL COILS PROVIDE ACTIVE FEEDBACK STABILIZATION OF RWM IN LOW ROTATION "ITER-LIKE" PLASMAS



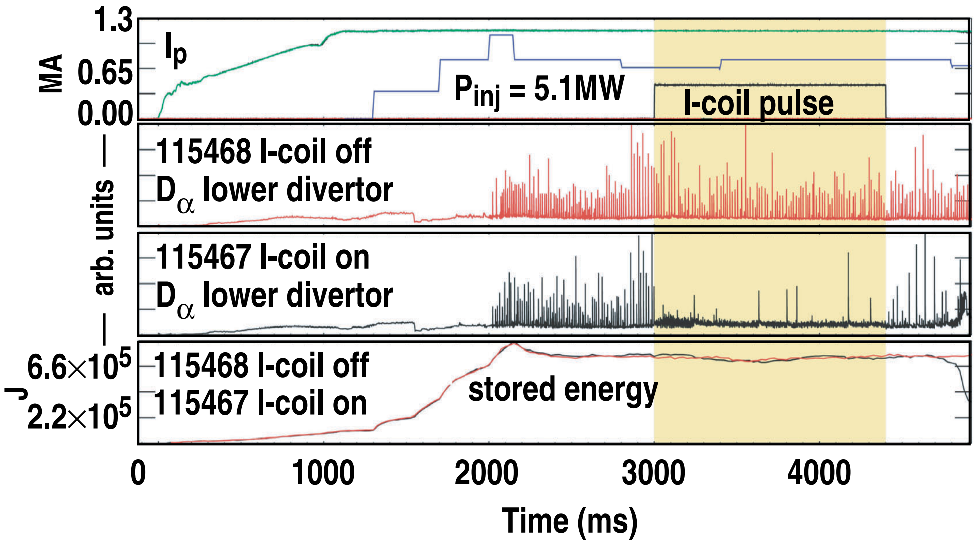
- **System upgrade planned to achieve RWM stabilization near ideal wall limit**
  - Low inductance stripline (< 1μH vs 20-40μH)
  - High bandwidth audio amplifiers
  - Low latency plasma control system (10μs vs 60μs)
  - External coils to provide low frequency feedback

INTERNAL COILS SYSTEM SUCCESSFULLY USED TO SUPPRESS LARGE ELMs

- n=3 magnetic field from I-coil perturbs plasma edge
- Relative phase of upper and lower coil sets affect ELM suppression



even up-down parity



- Significant reduction in large ELMs
- No degradation in core confinement or increase in core radiation
- Fast heat flux spikes from ELMs reduced at least a factor of 5

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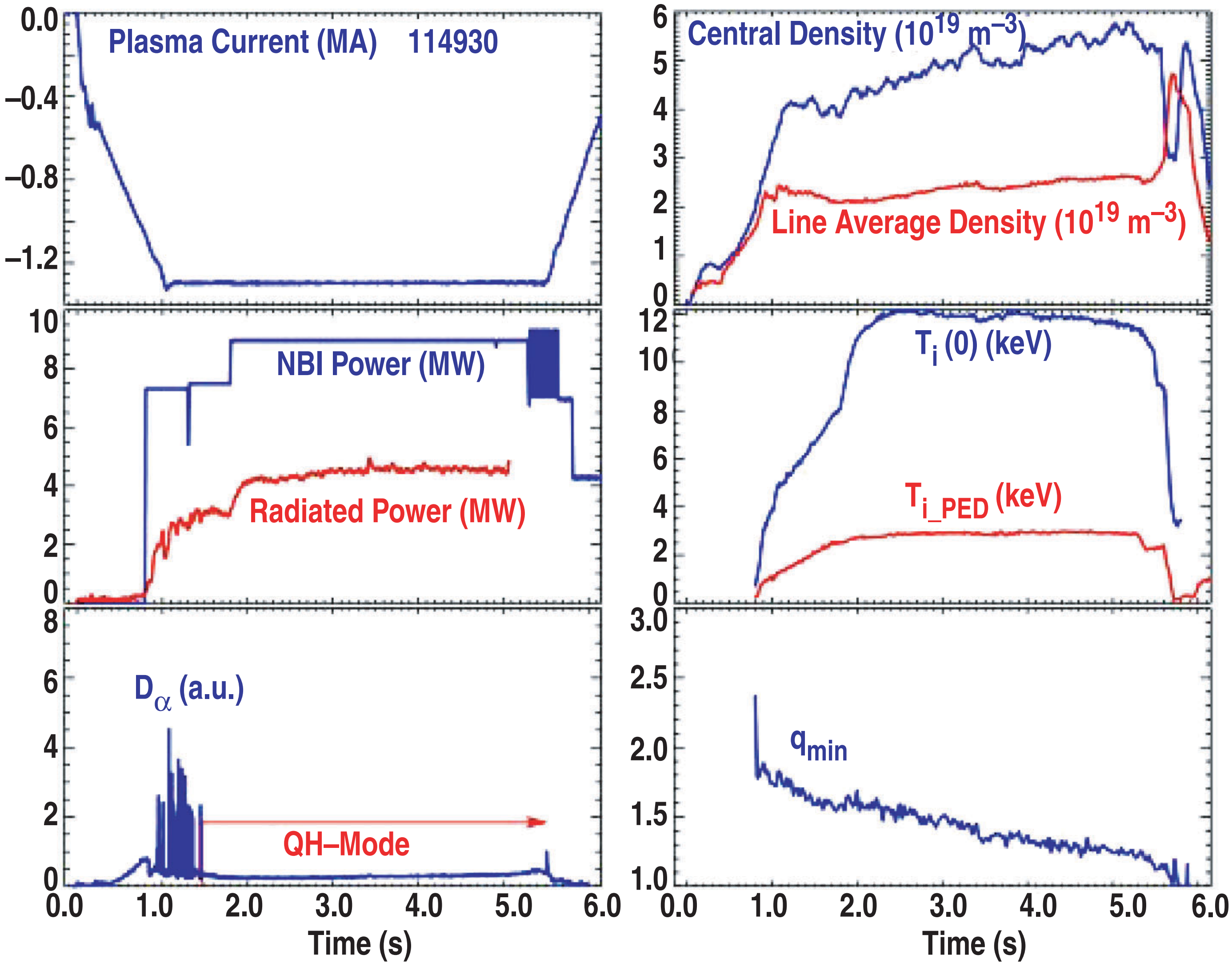
COUNTER NB INJECTION PRODUCES SUSTAINED ELM-FREE HIGH PERFORMANCE QH-MODE/QDB PLASMAS

- ELM-free edge with density & radiated power control maintained for 4s; $35\tau_E$
- QH-mode observed in other tokamaks JT-60U, JET, AUG
- Edge collisionality & β span projected ITER values
- ECH or ECCD reduces density peaking and impurity build up in core



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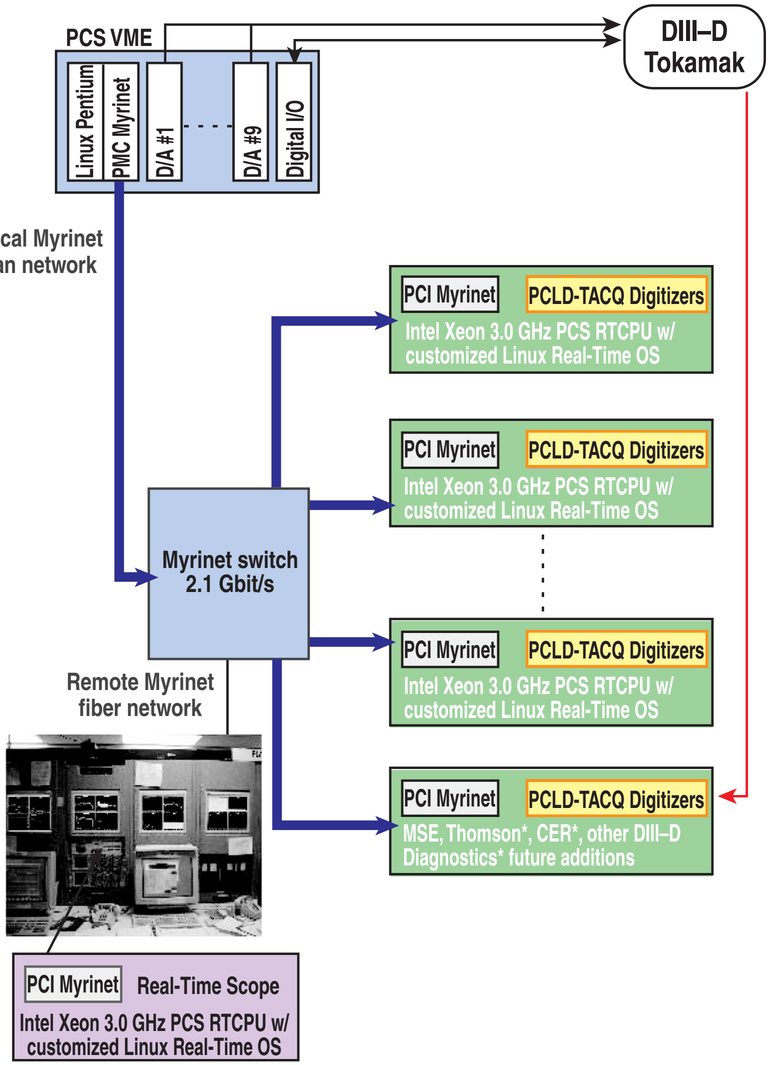
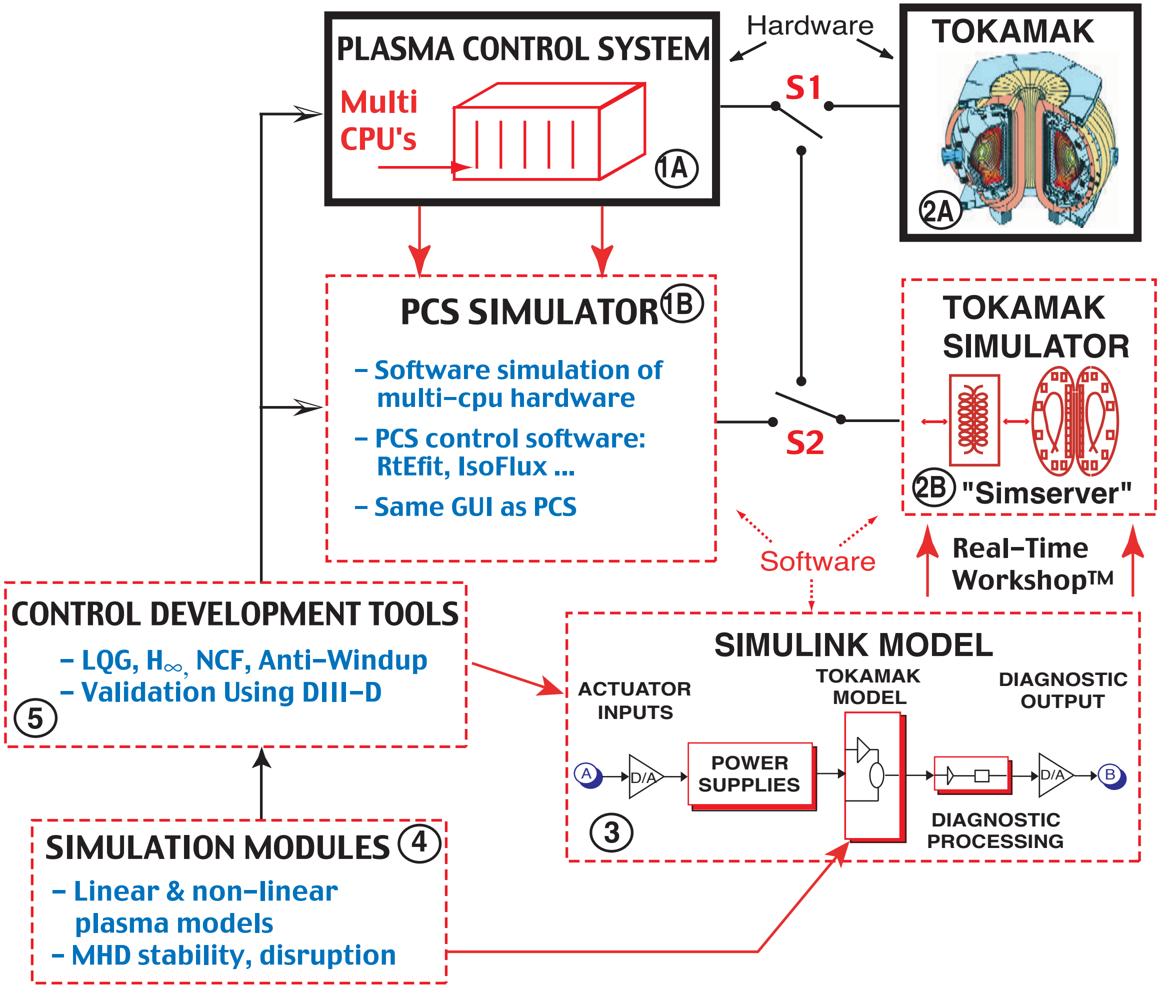
FLEXIBLE DIII–D PLASMA CONTROL SYSTEM SUPPORTS INTEGRATED PLASMA CONTROL



- Commercial, off the shelf components
  - — 2.4/3.0 GHz Intel Xeon cpus
  - — 2 Gb/s Myrinet network communication
  - — IDL-based graphical user interface
  - — D-TACQ solutions realtime data storage digitizers (32 channel, 16 bit, 250 kHz)
- True parallel computing architecture:
  - — 13 cpus running in parallel
- Linux-based OS:
  - — Customized for true realtime function w/o interrupts
- Software used world wide
  - — NSTX, MAST,
  - — KSTAR, EAST (under development)

DIII–D INTEGRATED PLASMA CONTROL MAKES EXTENSIVE USE OF SIMULATION AND DETAILED PHYSICS MODELS



PLASMA CONTROL SYSTEM ①A

TOKAMAK ②A

PCS SIMULATOR ①B
- Software simulation of multi–cpu hardware
- PCS control software: RtEfit, IsoFlux ...
- Same GUI as PCS

TOKAMAK SIMULATOR

②B "Simserver"

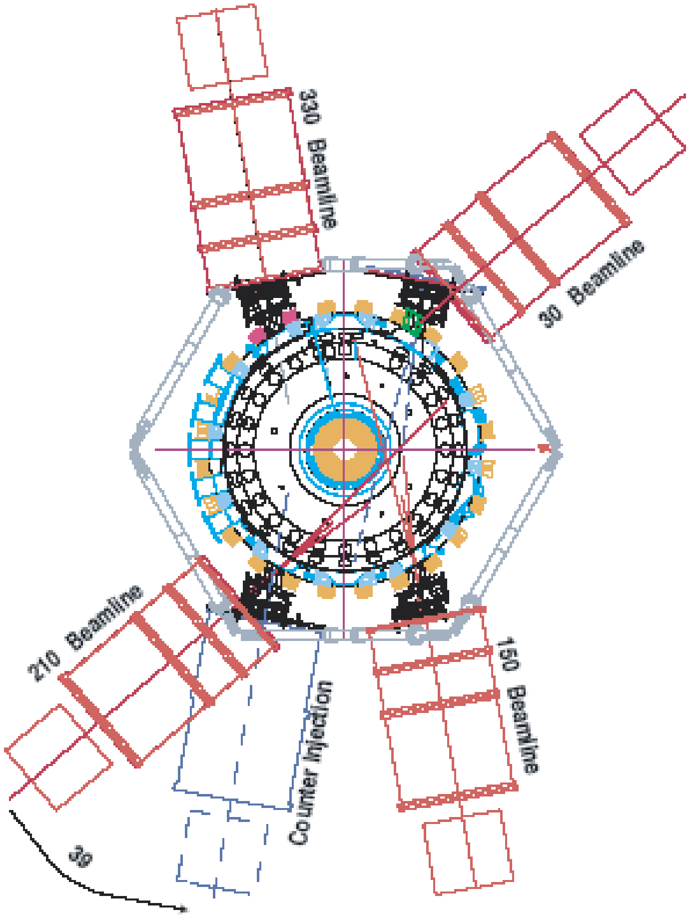
Real–Time Workshop™

CONTROL DEVELOPMENT TOOLS ⑤
- LQG, H_∞, NCF, Anti–Windup
- Validation Using DIII–D

SIMULINK MODEL ③

SIMULATION MODULES ④
- Linear & non–linear plasma models
- MHD stability, disruption

REVERSAL OF A NEUTRAL BEAMLINE WILL ENABLE NEW PHYSICS STUDIES AND IMPROVE PLASMA MEASUREMENTS



Control of momentum input with
6 co and 2 counter beams will permit:

- Study of RWM feedback stabiliztion at low rotation
- NTM stabilization with modulated ECCD
- Understanding physics of rotation
- Transport barrier control (separate control of Er and Shafranov shift)
- Separate measurements of Er and J(r) from MSE diagnostic

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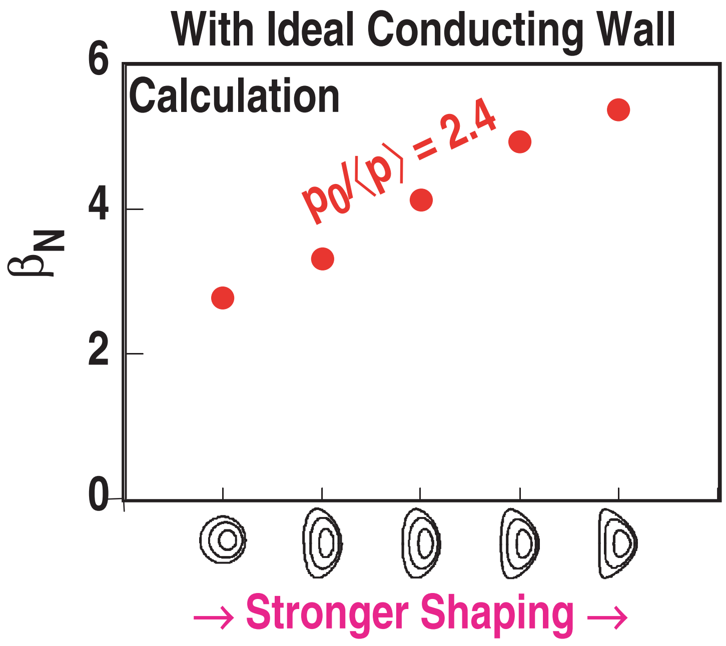
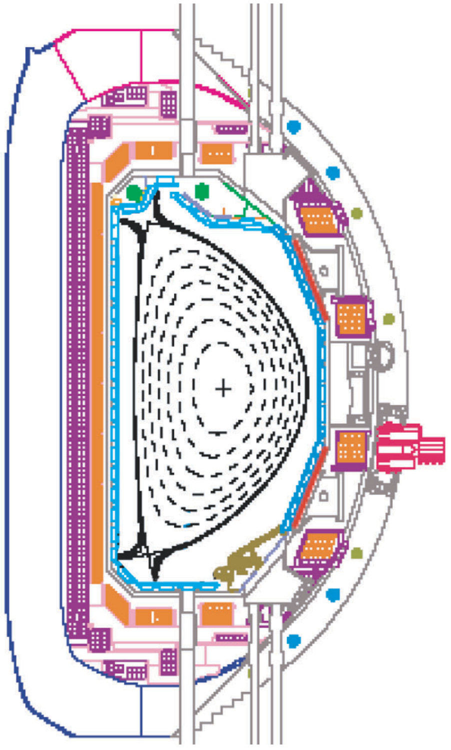
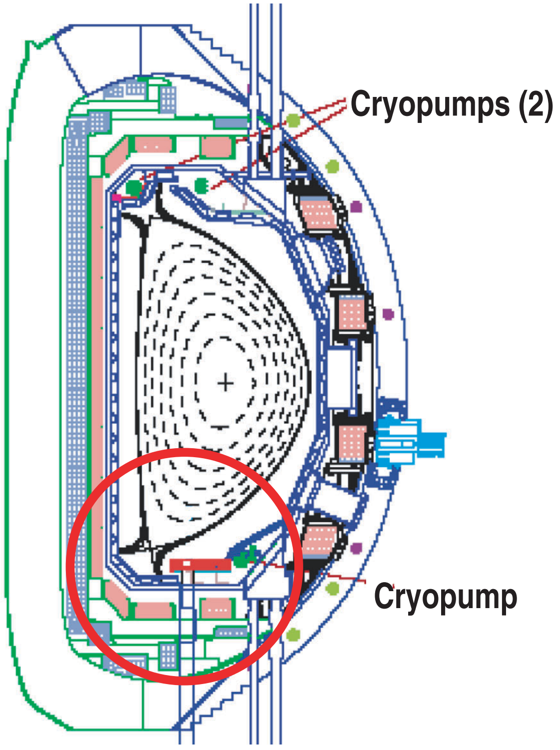
LOWER DIVERTOR WILL BE MODIFIED FOR DENSITY CONTROL OF HIGH TRIANGULARITY DOUBLE NULL DIVERTORS



- Present configuration only pumps 65% of particle input in high triangularity DND
- Extended lower baffle with existing cryopump pumps both ends of double null

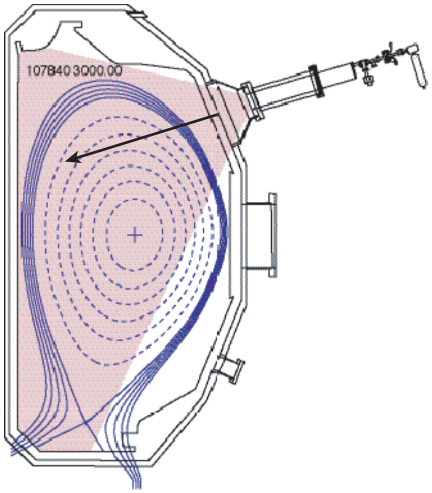
- High β MHD stability and confinement favor highly shaped double null divertor
- Density control is required to maximize EC current drive


EXISTING



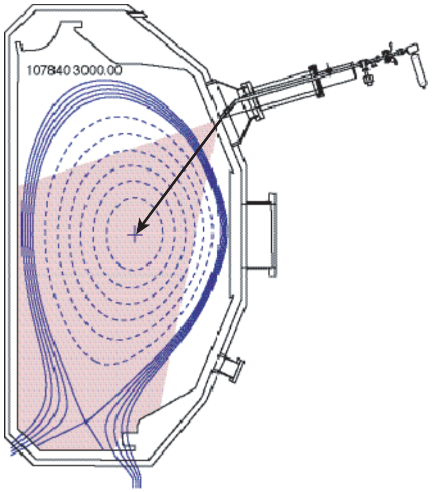
UPGRADED

HIGH PRESSURE GAS INJECTION SYSTEM WILL BE MODIFIED TO IMPROVE DISRUPTION MITIGATION



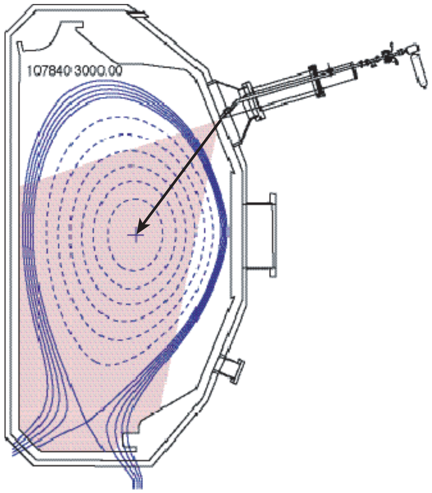
Open jet (Aug 03)

P_{jet} (ρ=1) ~ 0.04 atm
Fast (~1ms) rise time



Directed jet (Mar 04)

P_{jet} (ρ=1) ~ 0.02 atm
Slower (~3ms) rise time



Reduced back vol. (Oct 04)

P_{jet} (ρ=1) ~ 0.04 atm
Medium (~ 2ms) rise

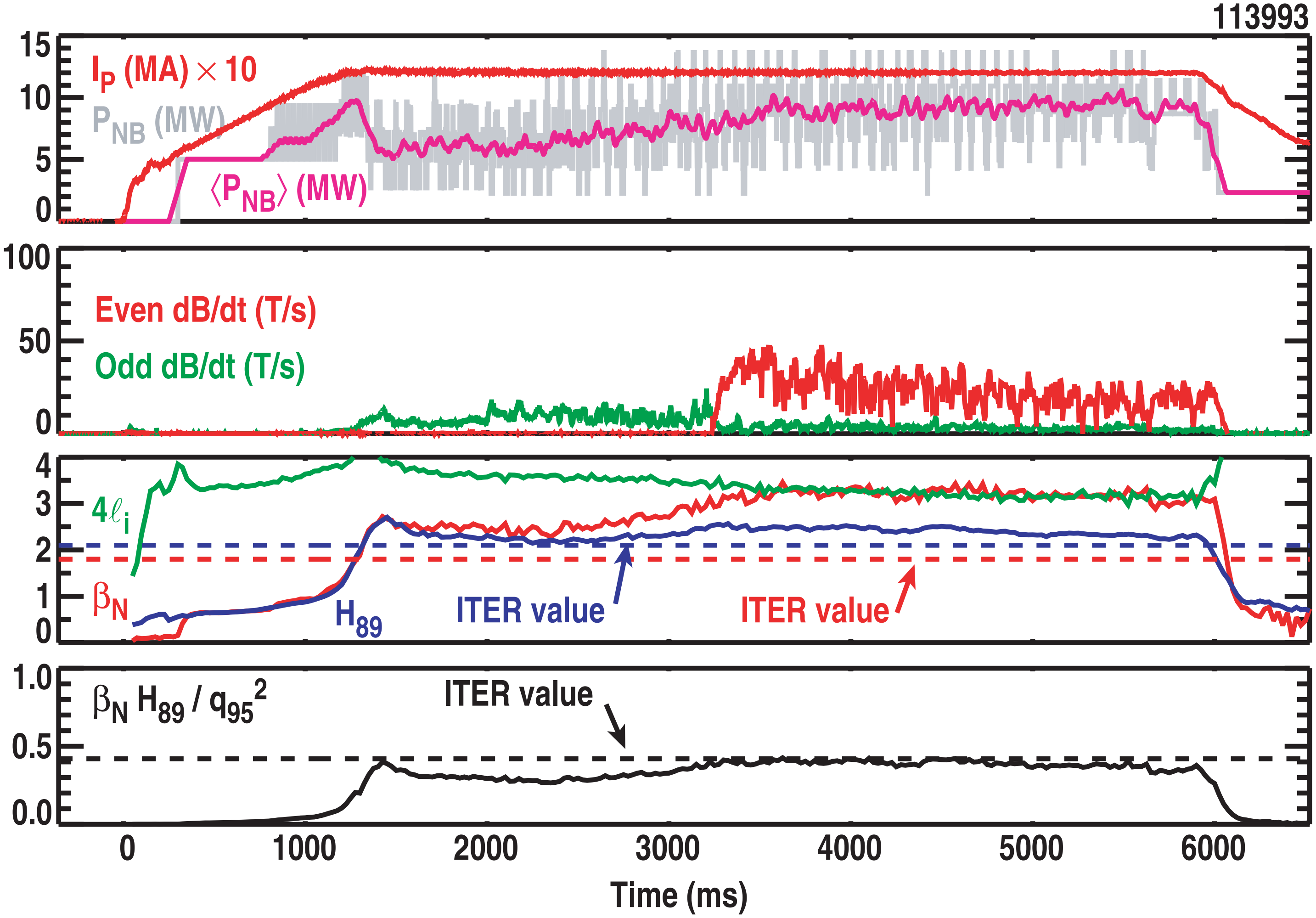
- Experiments show significant reduction in halo currents (2-3X) and divertor heat loads (~100% energy radiated)
- No observed runaway electrons due to high electron density (Ninj~500x$N_{e,plasma}$)
- Large variation (4X) in mitigation effectiveness seen with jet pressure

SUMMARY

- Improved control techniques have led to significant progress toward advanced tokamak operation
- 6 gyrotron EC system has provided current drive, heating, current and pressure profile control, NTM stabilization
- External coil set has provided reduced error field and permitted high plasma rotation for RWM stabilization
- A highly efficient and flexible internal coil set has provided RWM stabilization and ELM suppression
- Plasma Control System upgrade provides higher computing power for real time diagnostics and sophisticated control algorithms
- Planned upgrades include higher power EC, NB reversal for momentum control, and a new lower divertor for pumping high triangularity DND

DIII–D STATIONARY HYBRID SCENARIOS ARE DEVELOPING THE BASIS FOR LONG PULSE DISCHARGES IN ITER

- Similar hybrid scenarios are obtained in JET and ASDEX–U



Sustained operation with

$\beta_N = 3.2$

$H_{89} = 2.5$

$\beta_N H_{89} > 7.5$

Projection to ITER

$H_{98y2} = 1.6$

$Q_{FUS} = 10$

$\tau_{DUR} = 4500$ s

Experiments coordinated through International Tokamak Physics Activity

280–03/TST/wj